Shape Memory Alloy Based Caudal Fin for a Robotic Fish: Design, Fabrication, Control and Characterization

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ABSTRACT

A bio-mimetic fin embedded with shape memory alloy (SMA) wires has been developed. The design of the bio-mimetic fin is based on the musculature of a cuttlefish fin. The musculature of cuttlefish is studied. SMA is chosen as an actuator among the other smart material for its low actuation voltage and high power to weight ratio. A stepwise fabrication process of a bio-mimetic fin has been described for consistency and better performance. A series of tensile tests have been conducted to optimize the annealing temperature and the required pre-straining of the SMA wire actuating the developed fin. The optimum annealing temperature and the required pre-straining has been found to be 410° C and 4-6% respectively. The details of the heat treatment process followed have also been described. The maximum bending angle of 60° has been obtained for the developed bio-mimetic fin. The developed bio-mimetic fin has been integrated into a fish-inspired robotic structure to validate the capability of the developed biomimetic fin. The developed robotic fish can perform subcarangiform locomotion. The robot is capable of swimming in the forward direction as well as turning swimming mode. A control scheme for forward and turning swimming mode has been described. The developed robot is untethered and controlled wirelessly. The swimming speed and turning radius obtained are 7.6 cm/s and 45 cm respectively.

KEYWORDS

Robotic fish, shape memory alloy, smart material, soft robotics, SMA, underwater robot.

1. INTRODUCTION

Fishes are considered to be an ideal source of bio-inspiration for designing underwater robots owing to their locomotion adaptation to the aquatic environment. Fish-inspired robot designs, therefore, can provide better maneuverability and efficiency compared to their propeller based counterparts. A large number of fish-inspired robots have been designed and reported in the literature [1-5].

A vast majority of robotic fishes have their structures made up of steel, thermoplastic and thermosetting polymers and use servomotor or pneumatic/hydraulic actuators which make the overall design bulky, rigid and complicated. On the other hand, fishes often have a slender, sleek, flexible and often a hyper-redundant body structure. Similar to fishes, if robotic systems are made up of soft materials with redundant degrees of freedom then such robots can be used for performing complex tasks in an unstructured and cluttered environment. This paper reports a motor less and gearless shape-memory alloy actuated design of robotic fish which performs subcarangiform. The novelty of the design reported in this paper includes:

- Annealing temperature optimization of SMA wire.
- Development of SMA embedded bio-mimetic fin taking inspiration from cuttlefish musculature.
- Integration of bio-mimetic fin on an untethered neutrally buoyant underwater robotic platform.

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Smart materials are considered as an alternative to the conventional electro-mechanical devices for a miniature bio-inspired robot. Researchers have been focusing on the mechatronics design and control scheme of smart materials. Some of the smart materials found suitable for this kind of work include Piezo-based actuators, Electro-Active Polymers (EAP), Ionic Polymer-Metal Composites (IPMCs) and Shape Memory Alloy (SMA). MFCs developed by NASA [6] provide higher strain than conventional piezoelectric actuator. Piezoelectric ceramic is well known to operate at a higher frequency even at moderate voltage. EAP changes its shape in response to the electrical stimulus. shape memory alloy exhibits Shape Memory Effect (SME). SMA can memorize its shape which is done by a shape setting operation where SMA is heat treated at much higher temperature comparing to its phase transformation temperatures. After heat treatment, the SMA can be deformed to any shape and can be restored back to its pre-deformed shape by heating just above the phase transformation temperature. SMA has an advantage over the other smart materials due to the following characteristic: low actuating voltage 3~12 V, high power to weight ratio, high recovery stress, large energy density, low contraction time, silent operation and long operating cycles up to 10^6 cycles.

In this paper, taking inspiration from Cuttlefish musculature, we designed a three-layered caudal fin with a 600-micron thick flexible Polyethylene terephthalate (PET) layer sandwiched between two elastic silicone layers. We embedded a pair of pre-stretched SMA wires on both the silicone layers in an antagonistic configuration for the actuation of the developed robotic caudal fin. The musculature-based structure imparts flexibility while the use of SMA provides a continuous actuation of the developed caudal fin. We integrated the developed caudal fin on an untethered neutrally buoyant underwater robotic platform comprising of onboard power and control units. The developed untethered robotic platform performs subcarangiform locomotion and generates propulsion by the displacement of water employing the undulation of the SMA actuated caudal fin.

In comparison with any conventional motorized robot, a small-sized and low weight SMA based robotic fish is developed. The overall dimensions of the robot are 25.0 cm in length, 3.7 cm in width, and 6 cm in height. The head and the tail parts are 13.5 cm and 11.5 cm long respectively. The shell thickness of the head part is 3 mm. The overall mass of the robot is 230 gm. The power consumed by the developed fish robot is 4 Watt. The maximum swimming speed and minimum turning radius achieved by the robot are 0.3 BL/S and 1.8 BL. The robot employs 3 cells Lithium ion battery of 1500 mAh which is capable of providing enough current to the robot for swimming for about 2 hours. Onboard power is an issue for SMA-based robots as the efficiency of an SMA-based actuator is very low (<10%). Using SMA embedded bio-mimetic fin, fish robots of small size and low weight can be fabricated.

This paper is organized in the following order. In section 2, literature review of various robotic fish actuated by smart materials is reported. Section 3 describes the overview design of the developed robot. In section 4 heat treatment process of SMA and its characterization is done. Section 5 describes the fabrication process of SMA based actuator, its performance, and control. Section 6 reports the experimental result of the robot. Section 7 concludes the paper with a closing remark.

2. LITERATURE REVIEW

This section presents a summary of the literature review in the area of smart material based fish-inspired robots. Mainly the reported smart material used in the design of fish-inspired robots includes piezo-based actuators, Electro-Active Polymers (EAP), Ionic Polymer-Metal Composites (IPMCs) and Shape Memory Alloy (SMA).

Nguyen et al. used piezo-ceramic actuators driven tethered fish-like robot [7] which perform carangiform swimming, at operating voltage of 250V. Produces a force of 0.0048 N at an oscillation frequency of 1.4 Hz and swimming speed obtained is 0.08 Body Length/s (BL/s). Cen and Erturk also developed an untethered fish-like robot [8] which performed carangiform swimming pattern using MFCs actuator and generates a mean thrust force of 0.01 N at an oscillation frequency of 5 Hz, its swimming speed achieved is 0.3 Body Length/s. Piezo-based actuators are capable of generating high actuating stress at a higher frequency but its application is restricted by the problem of high voltage. Most of the swimming robots using piezo-based actuators are tethered for power supply. Shintake et al. developed a soft bio-mimetic robotic [9] fish based on dielectric elastomer actuators (DEAs) with a length of 150 mm and weight of 4.4g, it swims by body and/or caudal fin (BCF) propulsion, maximum swimming speed achieved 0.25 body length/second at 0.75 Hz undulation frequency.

Berlinger et al. developed an untethered modular type robotic fish [10] using dielectric elastomer actuator, it is capable of both planer and vertical swimming just by shifting its center of mass, maximum swimming speed achieved is 0.55 body length/second. Li et al. also developed [11] an untethered robotic fish using dielectric elastomer and ionically conductive hydrogel, this fish can swim at a speed of 0.69 body length/second. Kamamichi et al. developed a snake-like swimming robot using IPMC actuator [12] composed of three links connected by IPMC film operated at a voltage of 1-2 V and achieved swimming speed of 0.066 Body Length/s. ye et al. developed a bio-inspired robotic fish equipped with caudal fin [13], the caudal fin the propelled by IPMC actuator, maximum linear swimming speed achieved 12 mm/s and turning speed achieved 2.5 deg/s. Zheng et al. modeled a robotic fish [14] which is propelled by the hybrid tail, it consists of two tail joints actuated by a servo motor and IPMC soft actuator respectively, the servo motor generate the flapping motion for propulsion and IPMC actuator directs the propulsive force for steering. IPMC actuators are power efficient and has high actuation frequency, but its application in robotics are limited by the problem of low actuation force. Rajendran and Zhang developed a three-link robotic fish prototype [15] using a newly developed smart material supercoiled polymer (SCP) in antagonistic configuration and simulated the speed control algorithm using reinforcement learning.

SMA possesses an advantage over the other smart materials due to its higher energy density, low operating voltage, and high actuating force. SMA extensively used in various fields. Maeno and Hino developed a 20 DOFs miniature robotic arm using SMA [16]. AbuZaiter et al. developed a 3 DOFs micro-positioning stage driven by SMA [17]. Coral et al. made a robotic fish [18] inspired by black bass fish which exhibit a carangiform swimming mode, this robot used two SMA based linear actuator in antagonistic configuration with simple PID controller receive position feedback from flex sensor. Kim et al. developed a robotic fish inspired by ray fish [19], its pectoral fins are actuated by shape memory alloy, and it is able to swim at a speed of 0.26 body length/second. And there are several other robotic fish [20-22] which employed SMA as an actuator. Though many researchers have developed SMA based actuator for different robotic applications a proper mechanical design and fabrication process of SMA actuator based on the mechanical and thermal behavior of SMA wire is still an issue. A proper actuator design and proper fabrication process will improve the performance of the SMA actuator.

3. DESIGN OVERVIEW

This section provides an overview of our design. Our design is based on the biological design of musculature of cuttlefish fin.

3.1 Cuttlefish Fin Musculature

Fishes perform subcarangiform swimming through undulation of the caudal fin. This undulation takes place through sequential contraction of their muscle fiber. For designing a bio-mimetic caudal fin cuttlefish fin musculature can be considered as an ideal design inspiration as the musculature of the fin has been evolved over a course of a billion years for surviving in the aquatic environment. Instead of the skeleton, the cuttlefish comprises of a muscular hydrostat. Muscular hydrostat is a dense musculature which generates force and also provides strength for locomotion and movement. Cuttlefish swims with a strip-like fin extended along the body. The stipe-like fin produce a undulatory motion along its length which generate forward swimming thrust. Cuttlefish fin can be considered as an ideal design inspiration for artificial fin. The strip-like fin can be split up into a number of section along the body length. The undulatory motion of the fin is the combination of the bending of sections up and down in an undulatory pattern. Bending of sections can be taken as the inspiration for developing of a planer bio-mimetic bending fin.

A cross-sectional view of cuttlefish musculature is shown in figure 1. The cuttlefish musculature is separated into a dorsal and ventral region which is connected by an intermediate layer of median fascia connective tissue (MF). Ventral fascia (VF) and Dorsal fascia (DF) are located beneath the ventral and dorsal skin. A bunch of cross oblique connective tissue fiber (CT) spread across the three mutually perpendicular directions between median fascia and Ventral/Dorsal fascia. Both side of the median fascia transverse muscle fiber (T) starting from fin cartilage (FC) of the fin extended up to fin margin. In both the dorsal and ventral part of fin transverse muscle fibers (T) are separated by layers of dorso-ventral muscle fibers (DV) originated from median fascia extended up to dorsal fascia and ventral fascia. Apart from transverse muscle fibers and dorso-ventral muscle fibers, a layer of longitudinal muscle (L) fiber can be found on both the side of median fascia.

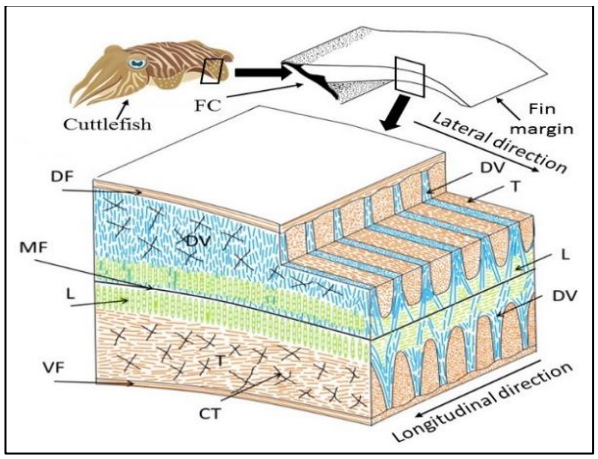


Figure 1: Musculature cross-section of cuttlefish fin

From the viewpoint of mechanical system, the fin is analogous to a prime mover. The fin includes muscle fiber, analogous to actuators, and connective tissue fiber, muscle fiber, and skin which are elastic elements. When transverse muscle fiber (T) contract along the lateral direction in the ventral region, fin bends ventrally and the ventral region shrink laterally. As the volume of the musculature is constant, the longitudinal muscle (L) and dorso-ventral (DV) muscle fibers in the ventral region elongate longitudinally. The transverse muscle fiber in the dorsal part is also elongated. The elongated muscle fibers and tissue fibers store the elastic energy. when the transverse muscle fiber (T) relieve the contraction the stored elastic energy in the muscle fibers and tissue fibers help fin to recover its shape.

3.2 Mechanical design

3.2.1 Design of bio-mimetic bending mechanism

The developed prototype is a fish-like robot with subcarangiform swimming pattern which include only a single flexible bending mechanism that mimics the motion of a caudal fin. SMA wires, like muscle fibers, are used for bending the continuous bending structure.

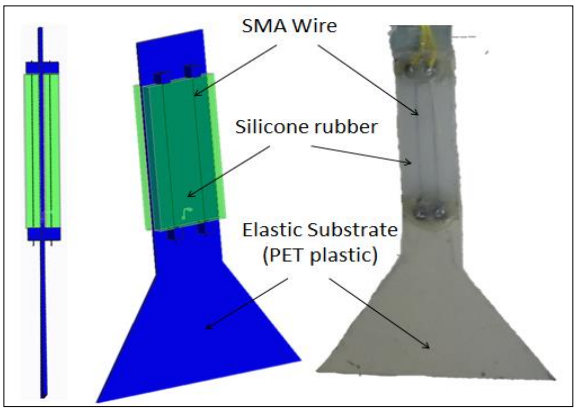


Figure 2: Bio-Mimetic Bending Mechanism

We have developed a flexible bending mechanism embedded with SMA wires (shown in figure 2). The backbone of the fin is made of Polyethylene terephthalate (PET) plastic of thickness 0.6 mm and size 90 × 25 mm. This plastic sheet is chosen for flexibility and high-impact resistance and acts as median connective fascia (MF) which stores the elastic energy during bending. SMA wire with diameter 0.2mm is used. The four SMA wire of length 50 mm is first pre-stretched by 4% and a pair of SMA wires are attached on both sides of the elastic substrate. The SMA wires on both sides of the elastic substrate are adhered to the substrate as well as thermally insulated from water via a silicone layer The silicone layer is analogous to the connective tissue in a fish.

SMA wire pairs are heated alternatively on both sides by a DC electric pulse resulting in a contraction of SMA wire longitudinally which causes bending of the structure. The elastic energy of the bending is stored in the elastics substrate and SMA wires of the other side which helps to regain its initial positions.

3.2.2 Bending principle of bio-mimetic bending mechanism:

Figure 3 shows the bending principle of the bio-mimetic fin. The SMA wire is attached parallelly with PET plastic and covered with silicone rubber. As the SMA stretched, it causes the PET plastic sheet to bend. Bending angle α is dependent on the contraction length ΔL and offset distance between PET plastic and SMA wire is d. bending angle is directly proportional to the contraction length ΔL and inversely proportional to the offset distance d.

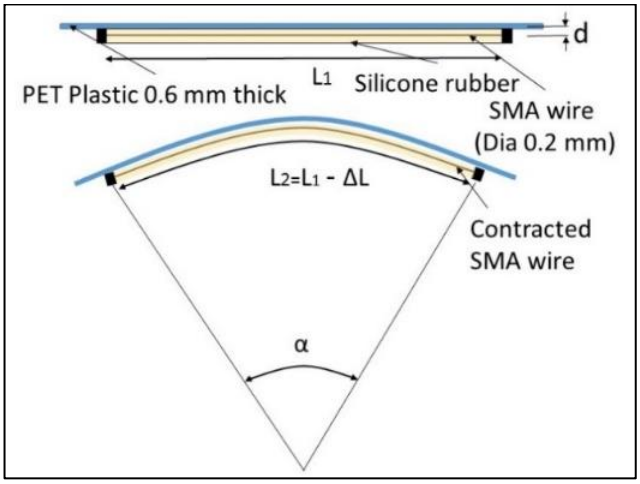


Figure 3: Principle of the bio-mimetic bending mechanism

3.2.3 Control, Power and Communication Systems

The cross-sectional view of the developed robotic fish prototype and its internal electrical components are shown the figure 4. The robotic fish prototype has two parts: the head part houses the electrical components and a SMA integrated tail part. The head portion is composed of rigid front and back shell. The head parts are made of ABS (Acrylonitrile-Butadiene-Styrene) thermoplastic polymer material fabricated on 3D printer. The front and back 3D printed shell are attached with the gasket in between; provide a waterproof enclosure for internal electronics. The tail part is the bio-mimetic caudal fin embedded with SMA.

As shown in figure 4 the untethered robotic fish prototype is equipped with three cells lithium-ion battery, Arduino Nano micro-control, RF module, electrical relay. The biomimetic fin is connected to the electrical relay which switches the battery power to fin sequentially. The control signal is generated by the Arduino Nano upon a command received from the RF module. The battery used here is capable of providing power to the robot for free swimming about 2 hours in a single battery cycle, due to lower power consumption. The overall dimensions of the robot are 26.5 cm in length, 3.7 cm in width, and 6 cm in height. The head part and tail part is 13.5 cm and 13 cm long respectively. The shell thickness of the head part is 3 mm. The weight of the robot is 230 gm.

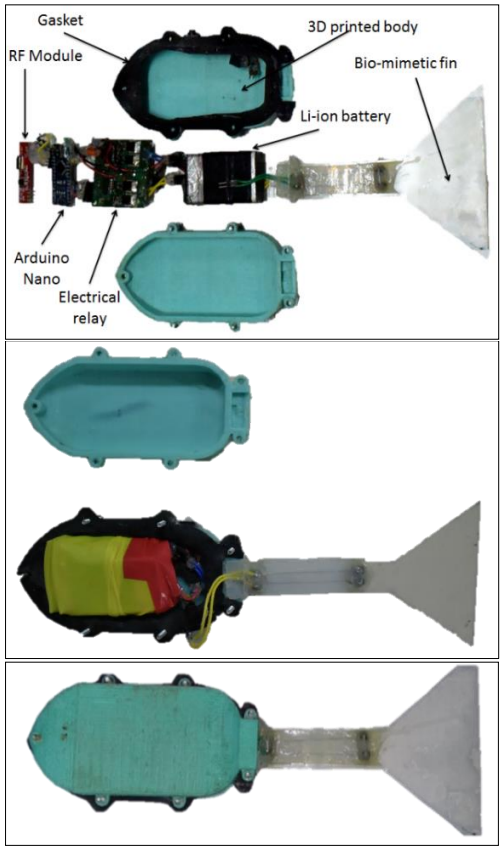


Figure 4: Robotic fish and cross-sectional view highlighting key internal components before and after assembly.

4. SMA SHAPE TRAINING AND CHARACTERIZATION

Commercially available Shape Memory Alloy (NiTi or Nitinol) are supplied as raw material. It does not have a shape memory effect. To memorize a certain shape, a shape setting operation is normally done. Where the raw SMA is heated treated at a much higher temperature. The heating treatment process and heating temperature are the crucial aspects of the heat treatment process. The shape memory effect highly depends on the heat treatment process and heating temperature. Annealing is normally performed for shape setting operation as it completely relieves the residual stress in SMA. We have studied the mechanical behavior of SMA under different annealing temperature. We found three trends that vary with annealing temperature.

- First, the detwinning force increases as annealing temperature decreases,
- Second, at the higher annealing temperature, the SMA loses its trained shape after some cycles and
- Any change in annealing time above 1 hr. doesn't have any significant effect in mechanical properties of SMA.

We found that annealing temperature below 450^0 C the shape lose is negligible. In our work, we have annealed the straight SMA wire at 410^0 C in the furnace for 2 hours and cooled it in furnace till it comes to room temperature.

4.1 Effect of annealing temperature on mechanical properties of SMA

Annealing temperature changes the mechanical properties of the SMA wire. Both the detwinning force and actuation force are varying with annealing temperature. Detwinning force is the external force which required to stretch the SMA wire and the actuation force is the generated tensile force by the SMA wire upon heating. Thus, the annealing temperature affects the work efficiency of the actuator when used as an antagonistic configuration. 50 mm long SMA wire is annealed at 6 different temperatures ranging from 390º C to 440º C with an increment of

100 C and both the detwinning force and actuation force are measured on the tensile test setup as shown in figure 5. One side of the wire is fixed with a load cell and other with nut-bolt arrangement to elongate the wire. Proper caution has been taken to prevent the twisting of wire while taking the measurement.

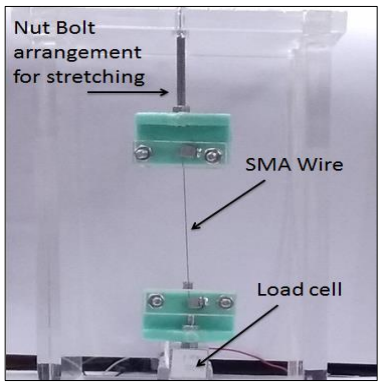


Figure 5: A simple tensile test setup for SMA wire.

4.1.1 Detwinning force:

Detwinning force is the important mechanical property of the SMA wire which affects the performance of the actuator. Six samples of SMA wire 50 mm length and 0.2 mm diameter annealed a six different temperature ranging from 390º C to 440º C. Wire is attached to fixture in the tensile test setup. An external force is applied to the wire by revolving the nut above the setup. The tensile force is recorded by load cell attached below. Stretching force is measured at a different strain. And the result is shown in figure 6. A clear trend can be seen from the result that the detwinning force is increased with a decrease in the annealing temperature. Detwinning force increased sharply above 4% strain.

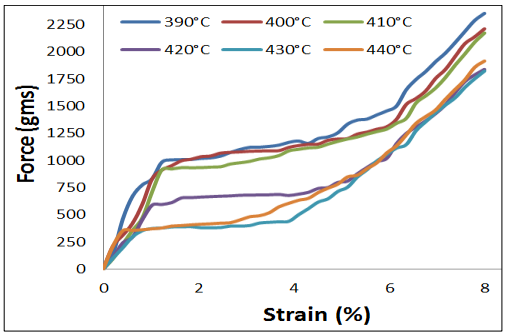


Figure 6: detwinning force at different annealing temperature

4.1.2 Actuation force:

Actuation force is also an important property of SMA wire. Actuation force at different strain is measured by simply heating the SMA wire by an external current source. The result is shown in figure 7. A clear trend is seen that the actuation force is increased with increase in annealing temperature. The actuation force is increased sharply up to a strain of 2% and beyond that, there is a gradual increase in actuation force.

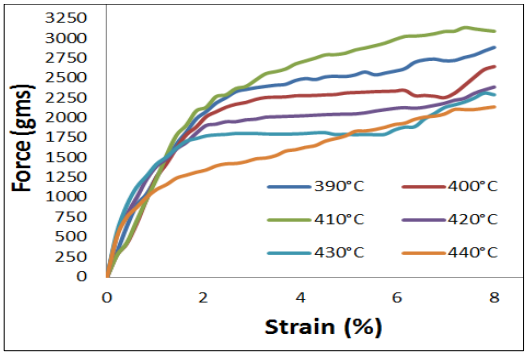


Figure 7: Actuation force at different annealing temperature

4.1.3 Effective Force

SMA based actuator work on the antagonistic configuration. Where the total effective forces which act on the structure of the actuator is the difference of actuation force and detwinning force. A plot of net effective force is derived by subtracting the detwinning force from actuating force at different strain for all the six temperatures as shown in figure 8. From the result, it can be seen that the effective force is maximum at a strain of 4% for most of the sample. The maximum net effective force is obtained for the sample annealed at 410º C temperature. This temperature can be considered as the optimum temperature for annealing for shape setting operation.

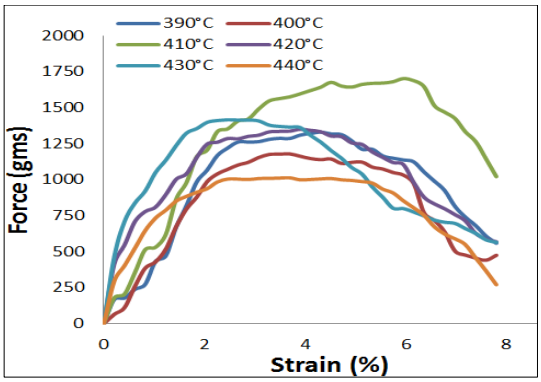


Figure 8: Net effective force at different annealing temperature

4.1.4 Analysis of Actuating Force

The actuating force of SMA wire has been estimated. The SMA wire is actuated by heating it through electrical current. A pulse of electrical current is supplied to the wire at different voltage and at different pulse time and the resulting force is obtained from the load cell. The actuating force depends on the actuating voltage and duration of the pulse. A series of experiments are carried out to determine the generating forces at different voltages and pulse duty cycles.

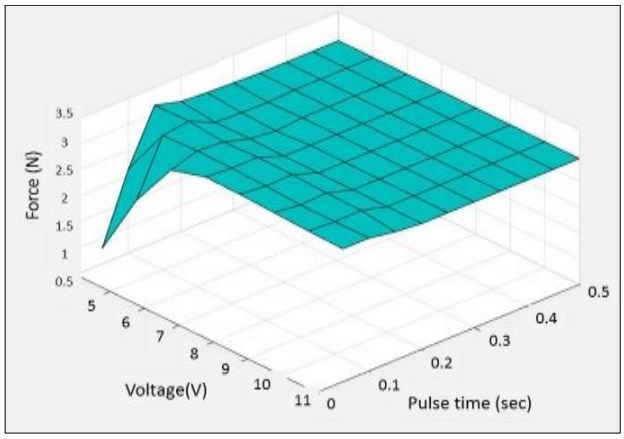


Figure 9: Analysis of Force at Different Voltage and Pulse Time

Figure 9 shows that the actuating force is relatively low at a lower voltage and at lower pulse duty cycle. After a certain voltage and pulse duty cycle, the actuating force is saturated and remains constant at a higher value of voltage and pulse duration. The maximum actuating force is obtained is 3.2 N at a voltage of 7V and duty cycle with an on-time of 0.15 Sec.

5. SHAPE MEMORY ALLOY (SMA) BASED ACTUATION AND CONTROL

5.1 Integration of SMA Wires in Robot Structure

A prototype of bio-mimetic fin embedded with SMA wire is developed (shown in figure 2). The developed bio-mimetic fin has three parts: Elastic substrate (PET plastic sheet), four SMA wire and Silicone rubber. For proper and stable functioning of the actuator a stepwise fabrication process is proposed (see figure 10)

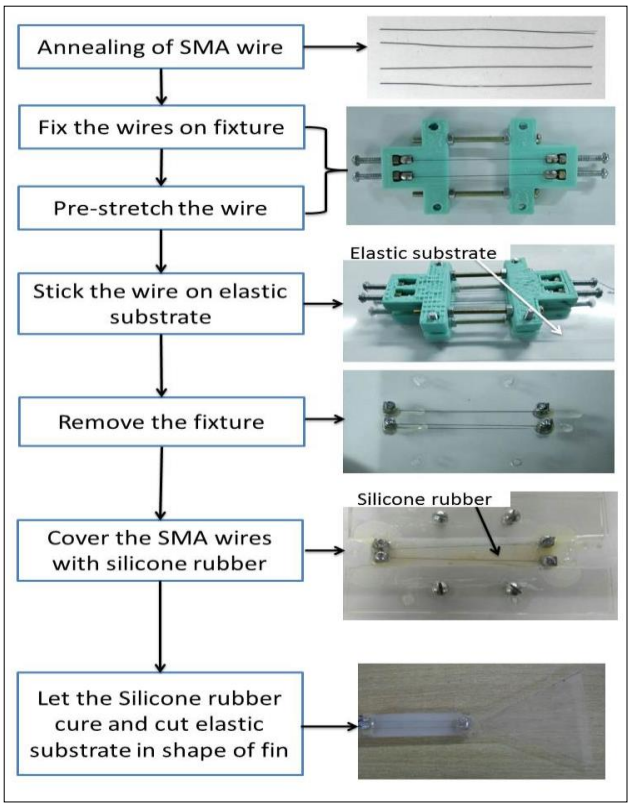

Annealing of SMA wire
Fix the wires on fixture
Pre-stretch the wire
Stick the wire on elastic substrate
Elastic substrate
Remove the fixture
Cover the SMA wires with silicone rubber
Silicone rubber
Let the Silicone rubber cure and cut elastic substrate in shape of fin

Figure 10: Flow chart of the fabrication process of bio-mimetic fin

In bio-mimetic fin four SMA wire of diameter 0.2 mm and length of 50 mm is used. The SMA wires are pre-heat treated at 410^0 in a furnace for 2 hr. The heat treatment process is explained in section VI. Then the SMA wires are mounted on a fixture for pre-stretching. The SMA wires are pre-stretched by 4 % by the fixture. The SMA wire along with the fixture is sticked on the elastic substrate. PET plastic of thickness 0.6 mm is chosen as the elastic substrate. The fixture is removed keeping the SMA wires stick on the elastic substrate. The SMA wire is covered with a layer silicone rubber (Anabond 666 RTV silicone) of thickness 3mm. The elastic modulus (E~0.25 GPa) of the silicone rubber is too small compared to the Elastic modulus (E ~ 2-4GPa) of the elastic substrate (PET plastic). It provides negligible resistance in bending. This silicone rubber clings the SMA wire with an elastic substrate and also provide the thermal insulation of wire from water which eliminated the need for external skin for insulation.

Table 1: Specification of bio-mimetic fin

The total length of the fin	100 mm
Width	20 mm
Length of SMA wire	50 mm
The diameter of SMA wire	0.2 mm
Length of the bending segment	52 mm
Weight	15 gm
The thickness of the silicone rubber	3 mm
The thickness of the elastic substrate	0.6 mm

5.2 Performance of The SMA Embedded Bending Actuator

A bio-mimetic fin embedded with SMA wire is developed and tested. Table 1 provides the specification of the fin. The voltage of 11 V with a pulse duration of 100 microseconds is employed for heating the SMA wires. After each pulse, a delay of 500 microseconds is given to cool down the SMA wire. Figure 11 shows the maximum bending angle achieved both side of the fin.

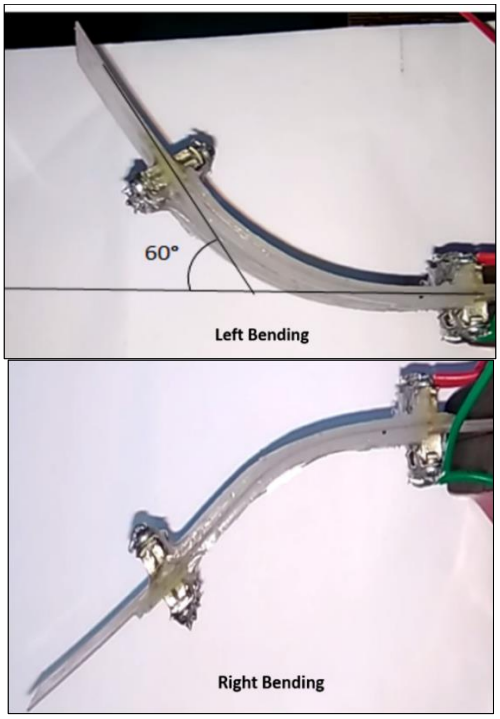


Figure 11: Bending of Bio-mimetic Fin

5.3 Control of Bio-mimetic Fin.

Figure 12 shows the control scheme of the actuator. The SMA wires are heated by a pulse of electrical current. A phase difference of 180º is maintained at both sides of the actuator for obtaining oscillation. The bending angle and the oscillation frequency can be controlled only be altering the T_{on} and T_{off} time. For higher $T_{on,}$ a higher bending angle is achieved while for a smaller T_{off} time higher oscillation frequency is achieved. The offset of the bending angle on both sides is generated by simply varying the T_{on} time.

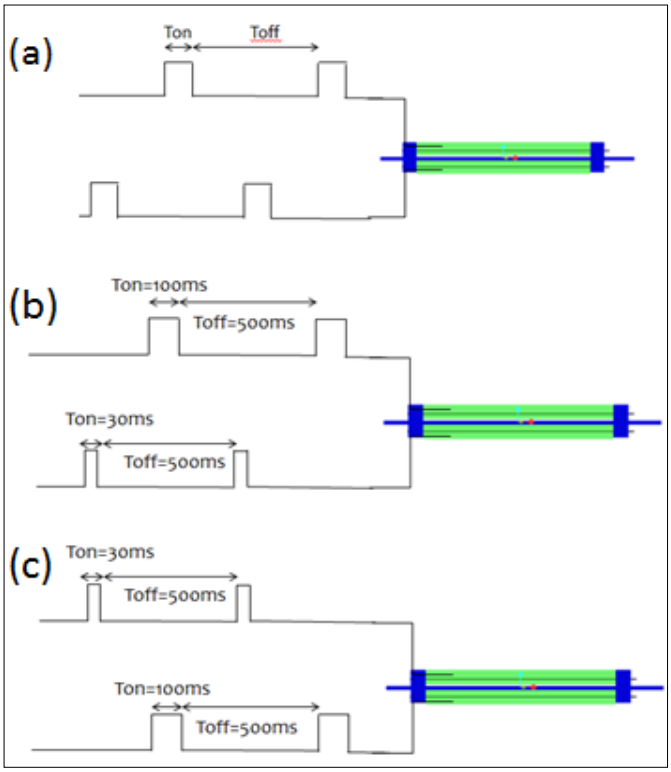


Figure 12: Control Scheme: a) Forward motion, b) Right turning, c) Left turning

6. SWIMMING PERFORMANCE OF ROBOT

The developed robotic fish can swim straight and can take left and right turn with single bio-mimetic fin. As shown in the figure 13. We have employed an open loop control method for different swimming mode. A sequence of the electrical pulse is given to the fin for performing different swimming mode as described in figure 12. For swimming forward, fin oscillates left and right. The robot moves forward by displacing water by the fin which produces a forward thrust force.

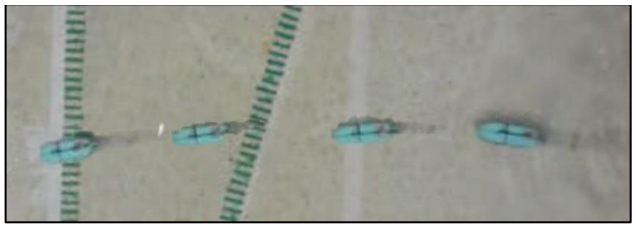
Turning of the fish robot can be done by any of the following three turning methods:

I. In this mode, the fin only oscillates to one side. It is the simplest turning method.

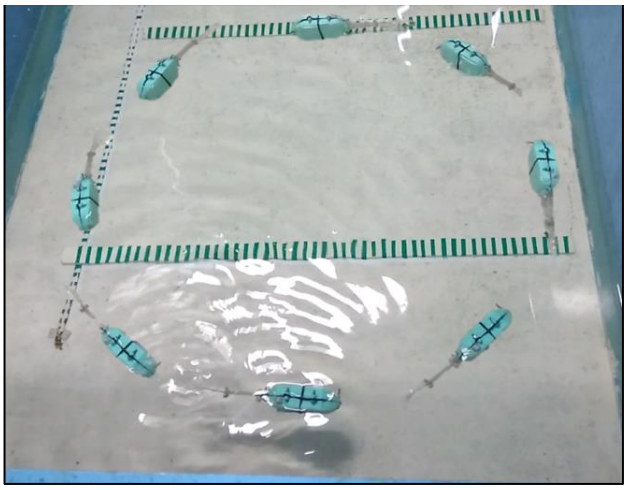
II. After achieving certain forward speed, the fin bends to one side and keep this state. The fish turn by hydrodynamic force. The fin acts like the rudder blade of the ship.

III. The fin bends back and forth keeping a certain offset angle from the stationary posture of the fin. In this mode, the turning radius is small and turning can be taken from the stationary state.

The swimming capabilities of the robot are investigated. The robotic fish is performing subcarangiform locomotion with a single fin. The swimming speed and turning radius obtained are 7.6 cm/s and 45 cm respectively.



a) Swimming forward



b) Turning left

Figure 13: Swimming modes of fish robot both forward and left turn.

7. CONCLUSION AND FUTURE WORK

A robotic fish of length 250 mm is developed which is operated by an SMA embedded bio-mimetic fin. This robot does not have any traditional actuator (motor, solenoid, servo motors). The design of the bio-mimetic fin is inspired by the musculature of cuttlefish fin. A stepwise fabrication process of the actuator is described for better and consistent performance of the actuator. The developed fin doesn't require any kind of external skin for the thermal insulation from the water. The body of the fish is fabricated in a 3D printer which also doesn't require any skin and provide a waterproof enclosure for the electronics. The maximum bending angle of 60º is obtained by the bio-mimetic fin. A series of tensile test is conducted to optimize the annealing temperature and percentage of pre-strain. The maximum net effective force is obtained for temperature 410ºC at a strain of 4-6 %. The robotic fish is untethered and the control signal is sent wirelessly. The robotic fish uses a 3 cell Li-ion battery which is capable of providing enough current for swimming about 30-40 minute. The robotic fish performed subcarangiform locomotion, the swimming speed and turning radius obtained are 7.6 cm/s and 45 cm respectively. The developed prototype can only swim on the water surface. Buoyancy-controlled robots have been reported [23] which can go inside the water and can hover at any location. In the future, buoyancy controlled swim bladders may be integrated to developed prototype to enable buoyancy-aided 3D locomotion inside water. The energy efficiency of robot that integrates SMA-based fin actuation and buoyancy control will be appreciably higher compared to the thruster-based or jet propulsion based swimming robots.

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